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Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall

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Abstract

For many coastal plain soils in the southeastern USA, high soil strength within subsurface horizons requires that deep tillage be performed to provide a suitable rooting environment for row crops such as maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.). We hypothesized that water filtering through the soil was recompacting it and that recompaction could be correlated with cumulative amount of rainfall since tillage. We measured cone indices in a structureless, fine loamy Acrisol near Florence, South Carolina, from 7 days to about 6 years after treatments were deep tilled. Measurements were made to a depth of 0.55 m at the point of maximum disruption of a bent-leg subsoiler (Paratill®) that tilled to a depth of 0.35–0.40 m. Regressions of cone indices with cumulative rainfall explained 67–91% of the recompaction and indicated that water filtering through the soil was causing the recompaction. Recompaction was slow, still taking place 6 years after tillage (the end of the experiment) probably because of controlled traffic or excessive disruption by the paratill. Recompaction was also temporarily greater for the 0.1–0.2 m depths when compared with that in the 0.25–0.35 m depths indicating that it was moving down the profile. Recompaction in other climates may be faster or slower depending on their cumulative rainfall relative to an annual amount of 900–1350 mm per year for this study and recompaction for structured soils may be faster or slower depending on whether the structure is stable or not. Though recompaction in this study was slow, tillage may still be necessary annually or seasonally because yield can be reduced even by incomplete recompaction that increases soil strength after a year or less.
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Keywords: Recompaction; Deep tillage; Rainfall; Subsoil hardpan; Coastal plain; Loamy sand; Penetration resistance

1. Introduction

High strengths in many coastal plain soils of the southeastern USA, especially in the E horizon, impede plant growth. High strengths diminish the positive effects of soil physical properties and reduce yield of row crops like maize, wheat, and sorghum (*Sorghum bicolor* (L.) Moench) (Arvidsson et al., 2001; Lapen et al., 2001; Radford et al., 2001). High strengths can be reduced and yield improved through deep tillage (Reeves and Mullins, 1995; Busscher et al., 2000; Raper et al., 2000). Though residual effects of deep tillage may be seen for years afterward (Munkholm et al., 2001), deep tillage for these coastal soils is recommended annually, either in spring (Threadgill, 1982; Busscher et al., 1986) or fall (Porter and Khalilian, 1995) or perhaps both (Frederick et al., 1998), because soil reconsolidation between growing

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seasons, although incomplete, can be enough to increase soil strengths enough to reduce maize, soybean, and wheat yields. In a previous study that used slit tillage and in-row subsoiling (Busscher et al., 1995), residual deep tillage effects were no longer seen after about 3 years, without controlled traffic under rainfall conditions that were slightly below average (978 mm per year for the study while the 15-year average was 1092 mm per year).

The problems of coastal plain sandy soils are further aggravated by low ($0.08\,g\,g^{-1}$) water holding capacities providing the plant with little available water. Low water holding capacities can lead to yield-reducing crop stresses for a number of row crops including maize, soybean and wheat when there is no rain for 2 weeks or less (Sadler and Camp, 1986). In the southeastern coastal plains, periods of 2 weeks or longer with no rainfall are recorded for most growing seasons (Sheridan et al., 1979). Deep tillage helps alleviate water stress by making more of the profile available for root exploration. Deep tillage in these soils involves non-inversion tillage to about 0.4 m, deep enough to disrupt the hardened E horizon.

In previous studies, we developed a series of tillage treatments where soil strength was linked to yield (Frederick et al., 1998; Busscher et al., 2000) and where times between tillage and measurement of soil strength ranged from 7 days to about 6 years. In these experiments, first the yields of wheat and soybean and later the yield of maize within the same plots decreased as soil strength increased through recompaction and as the time between tillage and crop growth increased. In these previous studies, recompaction was evident but it was not correlated to any variable other than changes induced by tillage or season-to-season effects. We hypothesized that the effect of water flowing through the profile was driving recompaction by reducing forces that cause the quasi-stable soil disposition after tillage (Coates, 2000; Or and Ghezzehei, 2002), especially for these structureless coastal sandy soils that soften when they become wet (Chartres et al., 1990). The objective of this study was to measure recompaction of deep-tilled plots over the 6-year term of the experiments and to correlate recompaction with amount of rainfall.

2. Materials and methods

2.1. Plot and treatment management

In spring 1993, before plot establishment, an experimental field at the Pee Dee Research and Education Center near Florence, SC was planted to soybean using conventional techniques of 0.76 m-spaced rows with in-row subsoiling. Between fall 1993 and 1996, the field was divided into plots that were planted to wheat and soybean double crops (Frederick et al., 1998). Between 1997 and 1999, the same plots were used to grow maize. Plots were 3 m wide and 15 m long. Plots were immediately adjacent to one another; data were taken across mid-plot rows.

Plots were located on a Goldsboro loamy sand (fine loamy Acrisol or fine loamy, siliceous, thermic Aquic Kandiudult) that had an E horizon below the plow layer. The Goldsboro series consisted of very deep, moderately permeable, moderately well drained soil that formed in coastal plain sediments. The Goldsboro soil had Ap and E horizons that were typically loamy sands, 0–0.25 m in thickness, $0.2–0.8\,g\,kg^{-1}$ in clay content, less than $20\,g\,kg^{-1}$ organic matter, and $1–3\,cmol\,kg^{-1}$ in cation exchange capacity.

On the day before planting, two surface tillage and four deep tillage treatments were imposed on the plots; soil water contents were at or below field capacity (Busscher et al., 2000). Surface tillage treatments involved disking the plots twice before planting (once in each direction along the 15 m length) or not disking. Between 1993 and 1996, the four deep tillage treatments involved no deep tilling (N), deep tilling every spring (S), every fall (F), and both spring and fall (B). Between 1997 and 1999, deep tillage frequency was reduced but treatments were tilled at least once every 3 years (Table 1) because, after that amount of time, deep tillage was deemed no longer effective, as previously seen under 978 mm per year of rain without controlled traffic (Busscher et al., 1995). All treatments were replicated four times in a randomized complete block design.

Surface tillage, deep tillage, and planting were done in separate operations but followed the same wheel tracks as closely as possible. Surface tillage was done with a 3 m-wide Tufline disk (Tufline Mfg. Co., Columbus, GA) pulled by a John Deere 4230 (Deere and Co., Moline, IL) 75 kW tractor weighing

Table 1
Approximate time interval between deep tillage and planting for the four deep tillage treatments of the maize experiment where in the wheat–soybean experiment B was deep tilled in both spring and fall, F in fall only, S in spring only, and N was not tilled since the year before the beginning of the experiment

Date of tillage	Time interval (years)			
	B	F	S	N
1 April 1997	0	1.5	1	No tillage
31 March 1998	0	2.5	2	No tillage
5 April 1999	1	0	3	No tillage

4.75 Mg with wheels on 1.6 m centers. Deep tillage was done with a four-shank bent-leg subsoiler (Paratill®, Tye Co., Lockney, TX). The paratill was pulled with a Case 2670 (Case-IH, Racine, WI) 165 kW, 4-wheel-drive tractor weighing 8.05 Mg with dual front and rear wheels on 1.9 and 3.1 m centers. Shanks were set 0.66 m apart and deep-tilled soil to the bottom of the E horizon, 0.35–0.4 m deep.

Between 1993 and 1996, plots were planted to soft red winter wheat cultivar 'Northrup King Coker 9134' and 'Hagood' soybean, a Maturity Group VII cultivar. Both wheat and soybean were drilled in 0.19 m-spaced rows with a 3 m-wide John Deere 750 No-till Planter pulled by a Massey Ferguson 398 (Massey Ferguson, Inc., Des Moines, IA) 60 kW tractor weighing 3.15 Mg with wheels on 1.9 m centers. Wheat was drilled on 18 November 1993, 23 November 1994, and 21 November 1995 at a within row rate of 65 seeds m^{-1} and harvested on 27 May 1994, 30 May 1995, and 24 May 1996. Soybean were drilled on 30 May 1994, 1 June 1995, and 7 June 1996 at a within row rate of 13 seeds m^{-1} and harvested on 3 November 1994, 3 November 1995, and 8 November 1996.

When in wheat, grain was harvested with an Allis Chalmers (Deutz-Allis, Norcross, GA) F3 Gleaner with a 4 m-wide header with wheels on 2.4 m centers, weighing 5.9 Mg. When in soybean, grain was harvested with an IH (Case-IH, Racine, WI) 1420 axial flow combine with a 4 m-wide header with wheels on 2.3 ft centers, weighing 8.1 Mg. Harvesting equipment followed wheel tracks of the planting equipment as much as possible.

Between 1997 and 1999, plots were planted to maize (DeKalb 687) in 0.38 m row widths using a John Deere 750 drill in 1997 and an 8-row Monosem planter (A.T.I., Inc., Lenexa, KS) in 1998 and 1999. Maize was planted on 1 April 1997, 31 March 1998, and 5 April 1999 at a within row rate of 3 seed m^{-1} and harvested on 28 August 1997, 18 August 1998, and 24 August 1999. Grain was harvested with a IH (Case-IH, Racine, WI) 2366 combine with a 4.6 m-wide maize header with wheels on 3 m centers, weighing 11.5 t.

2.2. Soil measurements

Cone index data were taken with a 12.5 mm-diameter cone-tipped penetrometer (Carter, 1967) on 21 June 1994, 16 June 1995, and 13 June 1996 in soybean and on 20 December 1994 and 12 December 1995 in wheat and on 22 April 1997, 29 April 1998, and 13 April 1999 in maize. Cone indices were measured at 7–2141 days after tillage (Table 2). Cone indices were measured by a penetrometer pushed into the soil to a depth of 0.55 m at nine positions spaced 95 mm apart starting at the middle of the plot and moving outward to one side of the plot into a wheel track. Cone index data were digitized into the computer at 0.05 m depth intervals (Busscher et al., 1986) and log (base 10) transformed before analysis according to the recommendation of Cassel and Nelson (1979).

Gravimetric soil water content samples were taken along with cone indices. They were taken at the first and fifth positions of cone index readings. These two positions represent the non-wheel-track position between shanks and the point of deepest disruption by

Table 2
Timing interval between deep tillage and cone index measurement for the four deep tillage treatments where in the wheat–soybean experiment B was deep tilled in both spring and fall, F in fall only, S in spring only, and N was not tilled since the year before the beginning of the experiment

Date of measurement	Time interval (days)			
	B	F	S	N
21 June 1994	23	216	23	384
20 December 1994	28	28	205	566
16 June 1995	16	206	16	744
12 December 1995	22	22	195	923
13 June 1996	7	206	7	1107
22 April 1997	22	519	320	1420
29 April 1998	30	891	692	1792
13 April 1999	379	9	1041	2141

the paratill shank, respectively. Water contents were measured at 0.1 m depth intervals to the 0.6 m depth. These water contents were taken as representative of the plot. Rainfall data were collected at a weather station located approximately 700 m from the field plots.

Cone index data were analyzed using GLM (SAS, 2000) with tillage treatments as main effects, depth (and position when applicable) as a split, and water content as a continuous variable. Cone indices were regressed against cumulative rainfall using either GLM or TableCurve v3.05 (Jandel Scientific of SPSS, Inc., Chicago, IL). Data were tested for significance at the 5% level unless otherwise specified.

3. Results and discussion

3.1. Constraints

The zone of disruption from tillage decreased in size with increasing time between deep tillage and measurement of soil cone index, as also seen by Coelho et al. (2000). When data were analyzed by position across the row, fewer positions had significantly lower cone indices than the non-tilled treatment as time between tillage and measurement of cone index increased. We chose the position of maximum disruption, the center of the tilled zone, to analyze recompaction because at this position soil would take the longest time to recompact. It was also one of the positions where water content was measured along with the cone indices.

Data analyses were further confined to depths where cone indices changed significantly with time. This eliminated the top 0.05 m where cone indices had no consistent trend with time and the bottom 0.40–0.55 m where cone indices remained relatively unchanged because these depths were below tillage. The depths of analysis were 0.1–0.35 m: the tilled zone. The objective of tillage was to disrupt soil to the bottom of the E horizon at approximately 0.35–0.4 m depths.

We initially hypothesized that the major cause of recompaction would be water infiltrating through the profile as suggested by Coates (2000) and we suspected that the amount of infiltrating water would differ for different treatments, especially for the disked and non-disked tillage treatments because they affected the surface. However, cone index and water content differences between disked and not-disked treatments were not different in any of the analyses, either across the whole profile or limited to the point of maximum disruption. We, therefore, assumed that infiltration differences were not enough to cause significant differences and continued our analyses using cumulative rainfall and not infiltration but were aware that this may not prove valid for other soils or under other conditions. Also, if it does prove true that cumulative rainfall rather than infiltration can be correlated to recompaction, even if only for these sandy soils, analyses would be much easier for future cases and results would be more widely applicable. Rainfall data for the 6 years along with some distribution characteristics are shown in Table 3.

Table 3
Rainfall data for the years of the experiment where long term mean annual rainfall amount was 1162 mm for 1961–1990[a] and 1092 mm for 1986–2000[b]

Year	Total annual rainfall[c] (mm)	Rainfall rate		Percentage of events with rates 25.4 mm h^{-1} or higher
		Mean (mm h^{-1})	Error mean square	
1993	918	3.1	0.23	1.5
1994	1253	2.7	0.14	0.7
1995	1344	3.7	0.29	1.2
1996	1179	3.4	0.21	2.0
1997	999	2.6	0.14	1.0
1998	1061	3.3	0.19	1.1
1999	912	3.3	0.21	1.1

[a] http://water.dnr.state.sc.us/climate/sercc/.
[b] E.J. Sadler, Personal communication.
[c] Data from half hourly rate tables (E.J. Sadler, Personal communication) and monthly tables (http://water.dnr.state.sc.us/climate/sercc/).

Analyses with time between tillage and cone index measurement yielded essentially the same results as analyses with cumulative rainfall amounts. The two had essentially the same relationship with recompaction and the effects of the two could not be separated. The two were related to one another with a linear regression of 0.99 (data not shown). We continued the analyses assuming that cumulative rainfall (and not time) was effecting the recompaction.

Cone indices were not significantly related to water content differences as determined by GLM and regression analyses; even adding water content as an independent variable did not improve regressions. Cone index regressions with rainfall were made without regard to the differences in soil water content unless otherwise indicated.

3.2. Soil strength

When all data for the position of maximum disruption were analyzed together, cone indices were generally lower for treatments that had been tilled more recently (Table 4). For example, in 1999, cone index values ranged from 3.90 MPa for the treatment that was never tilled to 0.28 MPa for the treatment that was deep tilled 9 days before cone index measurements were made.

Cone indices for surface tillage treatments (disked and not-disked) did not differ. This was expected because treatments were measured at the point of maximum disruption from deep tillage; and, at that point, the effects of deep tillage would mask surface tillage. For the treatments that were not deep tilled, cone index differences near the surface were minimized by removal of data from the top 0.05 m of the profile.

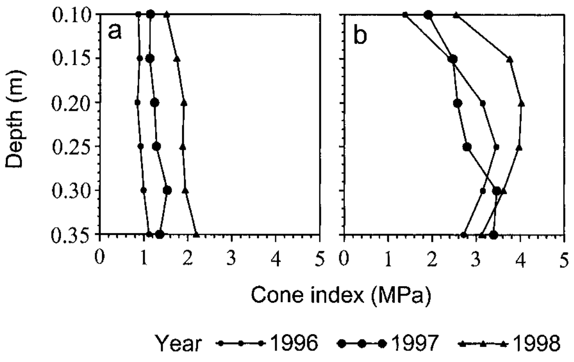

Fig. 1. Soil cone indices measured in 1996–1998 as a function of depth at the position of maximum disruption for the treatment deep tilled in 1996 (a) and for the treatment not deep tilled since 1993 (b).

3.3. Buildup of strength with rainfall

Buildup of cone index with cumulative rainfall can be seen on a treatment by treatment basis by comparing the treatment tilled in spring 1996 to the treatment not tilled during the entire experiment, i.e. not tilled since 1993 (Fig. 1). For the treatment tilled in spring 1996, rainfall amounts between time of tillage and measurement were 24.4, 851, and 2283 mm for 1996–1998. The treatment not tilled received the same

Table 4
Mean cone indices for the four deep tillage treatments corresponding to the times shown in Table 2 where in the wheat–soybean experiment B was deep tilled in both spring and fall, F in fall only, S in spring only, and N was not tilled since the year before the beginning of the experiment

Date of measurement	Cone index (MPa)			
	B	F	S	N
21 June 1994	0.25 (0.542)[a]	1.20 (1.11)	0.61 (0.850)	3.12 (1.51)
20 December 1994	0.62 (0.855)	0.54 (0.807)	0.81 (0.961)	1.98 (1.32)
16 June 1995	0.50 (0.777)	1.41 (1.18)	0.47 (0.753)	3.11 (1.51)
12 December 1995	0.44 (0.730)	0.45 (0.743)	1.10 (1.08)	2.16 (1.35)
13 June 1996	0.44 (0.730)	0.86 (0.982)	0.55 (0.815)	2.51 (1.42)
22 April 1997	0.49 (0.772)	1.05 (1.06)	0.96 (1.02)	2.64 (1.44)
29 April 1998	0.23 (0.516)	1.68 (1.25)	1.44 (1.19)	3.16 (1.51)
13 April 1999	1.63 (1.24)	0.28 (0.579)	2.90 (1.48)	3.90 (1.60)

[a] Numbers in parentheses are logs of the cone indices+0.1. Logs were used for analyses; adding 0.1 prevented the $\log_{10}$ from becoming zero. LSD for the difference among logs was 0.070.

amounts of rainfall plus 3721 mm from previous years. In Fig. 1, significant differences ($P < 0.05$) for the logs of the cone indices had an LSD of 0.98 which can be conservatively calculated as 0.25 MPa using a method reported in Johnson et al. (1994) to transform back to the original variable. Cone indices were significantly different between treatments. Cone indices generally increased over time, even for the treatment that had not been tilled since 1993.

When grouping all data (at the point of maximum disruption) together to analyze the buildup of strength with rainfall, we divided the profile into two zones based on horizon depths: 0.10, 0.15, and 0.20 m depths for the Ap horizon and 0.25, 0.30, and 0.35 m depths for the E horizon. Regressions of soil cone index with cumulative rainfall amount were developed for each horizon. Regression for the two horizons were compared with the method described by Johnson et al. (1994) and found to be not significantly different; so data were combined. The regression for the two horizons together (Fig. 2) demonstrated that recompaction was related to the square root of cumulative rainfall amount indicating a diminishing effect as rainfall (or time) increase. The square root of cumulative rainfall amount explained 75% of the increase in soil strength with time or recompaction.

The regression for the two horizons together (Fig. 2) also showed that cone indices were still increasing even after 6800 mm of rain or 6 years after tillage. Previously, Busscher et al. (1995) and Drewry and Paton (2000) reported that tilled and non-tilled

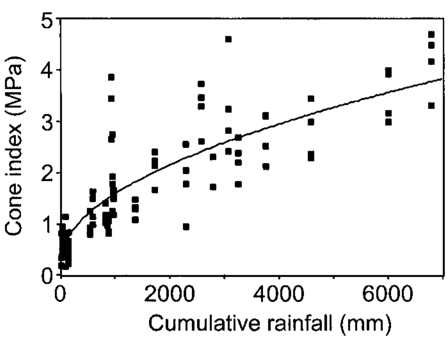

Fig. 2. Increase in cone index as a function of cumulative rainfall at the position of maximum disruption for data from both the Ap and E horizons and for the entire span of the experiment. The regression equation for the line is $CI = 0.219 + 0.0429R^{0.5}$, where CI is cone index and R is rainfall; the coefficient of determination is 0.75.

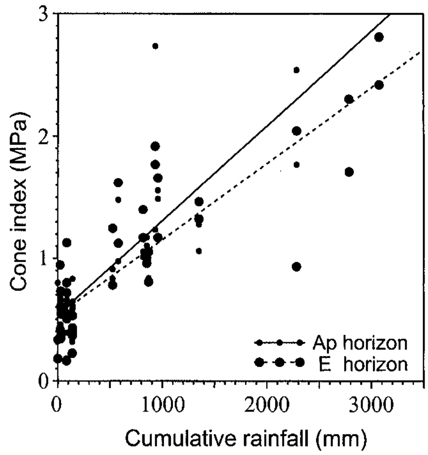

Fig. 3. Increase in cone index as a function of cumulative rainfall at the position of maximum disruption for only those treatments that were tilled during the experiment. The equations for the lines are: $CI = 0.535 + 0.000773R$, where CI is cone index and R is rainfall and where the coefficient of determination is 0.71 for the Ap horizon and $CI = 0.533 + 0.000621R$, where the coefficient of determination is 0.72 for the E horizon.

treatments were not significantly different after 3 years or less while Coates (2000) found that irrigated treatment differences disappeared after harvest. The reason that we continue to observe changes in this

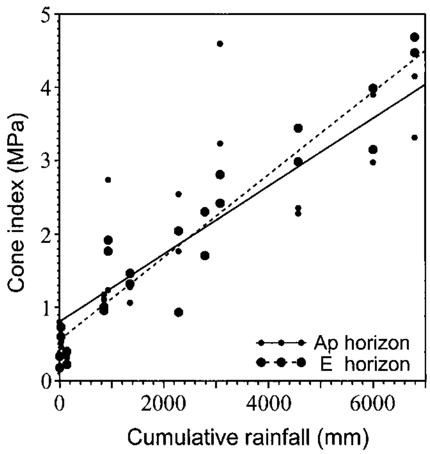

Fig. 4. Increase in cone index as a function of rainfall at the position of maximum disruption for all treatments in the last 3 years of the experiment. The equations for the lines are: $CI = 0.804 + 0.000462R$, where CI is cone index and R is rainfall and where the coefficient of determination is 0.67 for the Ap horizon and $CI = 0.557 + 0.000563R$, where the coefficient of determination is 0.91 for the E horizon.

Table 5
Selected values of mean cone indices for the Ap vs. E horizons showing higher cone indices in the Ap for about less than 750 mm of cumulative rainfall after tillage, mixed results between 750 and 3200 mm of cumulative rainfall after tillage, and higher cone indices in the E after about 3200 mm of cumulative rainfall

Horizon	Cumulative rainfall (mm)									
	30	84	142	815	932	1705	2786	3249	4571	6797
Cone index (MPa)										
Ap	0.54 a	0.56 a	0.63 a	0.98 b	1.60 a	1.87 a	1.58 a	1.88 b	2.26 b	3.50 b
E	0.35 b	0.27 b	0.46 b	1.24 a	1.66 a	2.10 a	1.78 a	2.47 a	3.08 a	4.35 a

study after 3 years or the reason that recompaction was slower than expected might be explained by successful use of controlled traffic. Another reason for slower recompaction could be that soil disruption with the paratill can be more thorough than other deep tillage implements (Karlen et al., 1991).

Data were re-analyzed with only the tilled treatments to look at recompaction in the short term. Eliminating non-tilled treatments reduced the range of times between tillage and measurement to 7 days to 2.85 years. Correspondingly, it reduced the range of rainfall amounts between tillage and measurement to 0–3076 mm. In this shorter term, regressions of cone indices as a function of cumulative rainfall were significantly different for the Ap and E horizons (Fig. 3). Regressions showed that the amount of cumulative rainfall between tillage and measurement explained 71 and 72% of the recompaction for the Ap and E horizons, respectively. The rate of recompaction for the lower horizon was slower than for the surface horizon, as seen by the smaller slope of its regression line. Since the surface horizon was affected by rainfall first, it was quicker to recompact; cone indices increased more there at first than deeper in the soil. As a side note, the fact that linear regressions could be used for the data in Fig. 3 was an indicator that recompaction was estimated as constant over this smaller time period and incomplete. Recompaction did not give a curvilinear fit which in Fig. 2 showed a decreasing rate of recompaction over a larger amount of cumulative rainfall or a longer period of time.

3.4. *Temporary higher recompaction in the shallower horizon*

Since a deeper horizon is usually more compacted than a shallower one, especially when the deeper one is a hardpan, greater recompaction in the shallower horizon was probably temporary, as also seen by Drewry and Paton (2000). This was verified by the fact that the recompaction curves were not significantly different when data for the longer time period was analyzed above. The temporary nature of higher compaction for the shallower horizon was also verified both by analyzing data for only the last 3 years (the maize experiment, Fig. 4) and by analyzing cone-index buildup as a function of increasing amount of cumulative rainfall. For the last 3 years, treatments had cumulative rainfall amounts between tillage and cone index measurement ranging from 0 to 6797 mm over a range of times from 9 to 2141 days. When estimated by linear regression, cone indices for the deeper horizon started out lower than for the shallower horizon (Fig. 4) and increased at a greater rate than the shallower horizon equaling the compaction of the shallower horizon at about 2500 mm of rain (about 2.5 years); they were higher than for the shallower horizon after that. The temporary nature of higher recompaction at shallower depths was also partially verified using GLM (SAS, 2000) to analyze cone indices by rainfall amount as a function of depth. Shallower depths had higher cone indices for most cases in the first 750 mm of rain, lower depths had higher cone indices for most cases after 3200 mm of rain, and results in between were mixed (Table 5).

4. Conclusions

The amount of cumulative rainfall between deep tillage and measurement of soil cone index explained 67–91% of the increase in cone index (recompaction) for treatments that were in wheat–soybean double crop for 3 years and then in maize for 3 years.

Over the 6 years of the study, regression showed that cone index increased with the square root of cumulative rainfall amount, indicating that recompaction rate was decreasing with increasing amounts of cumulative rainfall or with increasing time. It also showed that cone index was still increasing at the end of the experiment. In previous studies, recompaction of subsoiled coastal plain soil was complete after 3 years. The longer time for recompaction in this study was possibly induced by limiting the trafficked areas in the plots or by disrupting the soil more thoroughly with the paratill than with previous subsoilers.

Cone index was temporarily higher in the shallower horizon than the deeper horizon. This was probably the result of rain recompacting the surface horizon before recompacting the deeper horizon.

Since higher cone index has been associated with lower yield, slower recompaction would indicate higher yields for treatments recompacting more slowly; but slower recompaction does not mean that yields would be maximized. In a related study on the same plots, Frederick et al. (1998) showed that deep tillage twice a year (for double-cropped wheat and soybean) improved yield over deep tilling annually, while not deep tilling yielded the least. Also, for these soils that require deep tillage to loosen a root-restricting hardpan, even 1 year after deep tillage, mean cone indices averaged across the whole profile (data not shown) were as high as 1.5–1.7 MPa when corrected to $0.13\,\mathrm{g\,g^{-1}}$ water content (Busscher et al., 1997) and at or above a root-limiting value of 2 MPa (Taylor and Gardner, 1963; Blanchar et al., 1978) before correction.

These recompaction results were developed on unstructured sandy coastal soils. In soils with structure, recompaction can be complicated by inter- and intra-aggregate dynamics. Recompaction can also be affected by surface sealing or structural stability that can reduce or increase the amount of water filtering through the soil. It would be interesting to compare these results with results from dryer regions which might separate differences between the effects on recompaction of time and cumulative rainfall which were highly correlated.

In future studies, these results on recompaction rate can be combined with information on yield reduction as a result of increased compaction and information on cumulative rainfall predictions to help producers make management decisions on frequency of deep tillage.

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